RevMexAA (Serie de Conferencias), **6**, 87–89 (1997)

ISO OBSERVATIONS OF STARBURST AND ULTRALUMINOUS GALAXIES

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RESUMEN

Se reportan las primeras observaciones espectroscópicas en galaxias "starbursts" y "ultraluminosas" del Infrared Space Observatory (ISO). El amplio rango de especies iónicas, neutras y moleculares que emiten en el IR permiten estudiar las condiciones físicas de las regiones circumnucleares de estas galaxias y determinar las densidades del gas y las temperaturas de las estrellas excitadoras. Con la ayuda de modelos teóricos se examinan las fuentes centrales para discriminar entre emisión estelar y procesos no-térmicos, y restringir los modelos actuales sobre núcleos de galaxias.

ABSTRACT

We report first results on Infrared Space Observatory (ISO) spectroscopic observations of Starburst and Ultraluminous Galaxies. Observations of a wide range of ionic, atomic, and molecular infrared lines enable us to explore in detail the physical conditions in the circumnuclear regions of these galaxies, and to determine, as a first step, parameters such as gas densities and temperatures of ionizing stars. With the help of theoretical modeling this multi-line spectroscopic database is used to further probe the central emission mechanism, discriminate between stellar and non-thermal processes and finally constrain the current models of galactic nuclei.

Key words: **GALAXIES: STARBURST — INFRARED: GALAXIES**

1. INTRODUCTION

The galaxies studied for this work are representative examples of four classes: NGC 3256 is a luminous merger at 37 Mpc with a total luminosity (8-1000 μm) of 3×10^{11} $L_\odot$ (Sargent, Sanders, & Phillips 1989). Strong and extended 10μm emission provides direct evidence for nuclear starburst activity (Graham et al. 1984). NGC 4038/39 is a typical example of an interacting pair of gas and dust rich spiral galaxies. Evidence for ongoing and extensive star formation comes from observations in the so called 'overlap region' (e.g., Whitmore & Schweizer 1995). The present observations refer to this overlap region. NGC 5253 is a nearby 3.7 Mpc amorphous galaxy with a possible underlying dwarf elliptical galaxy (Lumsden, Puxley, & Doherty 1994). Finally, Arp 220 is the nearest and most well studied example of Ultraluminous *IRAS* Galaxies ($L\geq 10^{12}$ $L_\odot$). The mechanism responsible for the enormous amounts of energy released is not clear yet. A putative black hole may co-exist with an ongoing starburst, however there is more convincing evidence that the observed luminosity could be attributed to the latter mechanism.

Here we present an initial analysis based on ionic fine-structure lines and rotational H_2 lines detected by the Short Wavelength Spectrometer (SWS) on board ISO. An example of ISO-SWS spectra for NGC 3256 is shown in Figure 1. The full spectra for each galaxy and a more detailed analysis of their properties can be found in: Rigopoulou et al. (1996) for NGC 3256, Kunze et al. (1996) NGC 4038/39, Sturm et al. (1996) Arp 220, together with a discussion on *IRAS* luminous galaxies in Lutz et al. (1996).

2. PHYSICAL PROPERTIES OF THE IONIZED GAS

We probe the physical properties of the ionized emitting regions based on the fine structure lines observed. The local electron density of the ionized gas is measured by the ratio of the two [S III] 18 and 33 μm lines, since this ratio is sensitive to changes in the electron density for $100\leq n_e\leq 10^4$ cm^{-3}. For the two starburst galaxies, NGC 3256 and NGC 4038/39 and the dwarf NGC 5253, all the electron densities are low of the order of a few$\times10^2$ cm^{-3}. In the case of Arp 220, the upper limit of 0.5 also indicates that these lines arise in low density regions, too.

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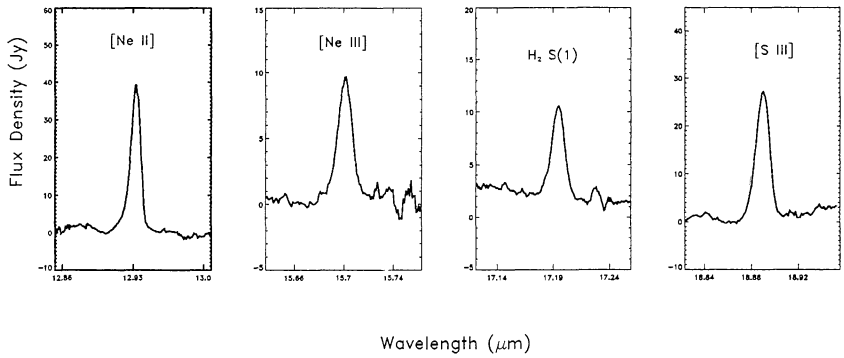

Fig. 1. NGC 3256 ISO-SWS spectra.

3. EXTINCTION

The extinction in these galaxies is determined from the observed H I recombination lines. Assuming the validity of case B for the observed recombination spectrum, an A_V of ≈ 35 is infered for NGC 3256, while a slightly higher value of A_V of ≈ 70 is derived for NGC 4038/39, in both cases assuming a mixed gas/dust model.

In the case of Arp 220, the dust/gas mixed model, even at the high optical depth limit ($\tau_V \rightarrow \infty$), cannot reproduce the H I recombination lines observed by ISO. Thus, as pointed out by Sturm et al. (1996) it is possible that in Arp 220 the extinction is better described by a screen model. Using the two hydrogen recombination lines observed by ISO, together with the Br_γ flux from the literature, an A_V of 40 mag is derived. Using the two [S III] lines an A_V of ≥ 59 is derived. The fact that ISO finds an extinction significantly higher than previous studies of Arp 220 removes one of the key constrains in previous attempts to model Arp 220 as a starburst.

4. STELLAR ATMOSPHERE MODELS

We have used the photoionization code CLOUDY version C84 (Ferland 1991), to determine the effective temperature of the ionization radiation field in the galaxies presented here. The assumption that the typical source size is comparable to the the overall size of the starburst, together with the electron density derived from the [S III] lines and the typical Lyman continuum luminosity, lead to an ionization parameter $\log(U) = -2.5$. The metallicities were set to solar. Our analysis is based on fine-structure line ratios of elements at different ionization stages, such as those of [Ne III](15.6 μm)/[Ne II](12.8 μm), [Ar III](8.9 μm)/[Ar II](6.9 μm), and [S IV](10.5 μm)/[S III](18.7 μm). These line ratios depend strongly on the exact input ionizing radiation field. We have used two different stellar atmosphere models, those of Kurucz (1992) and Sellmaier (1996) to investigate the effect of the ionizing radiation field on the fine-structure line ratios. The resulting diagnostic plot is shown in Figure 2(left).

The best-fitting effective temperature T_{eff} vary between 40 000 to 45 000 K. The only exception is NGC 5253, where detection of [O IV] 26 μm pushes the actual T_{eff} to values that could be as high as 53 000 K. The derived effective temperature needs then to be converted to an upper mass cutoff estimate. For a single star a T_{eff} of 44 000 K corresponds to O5 main sequence star with a mass of about 50 $M_\odot$. Figure 2(right) shows the T_{eff} - M relation for the galaxies presented here. However, the single star approximation is only a lower limit of the true upper mass cutoff. The next step would be to generate synthesized spectra from single star spectra weighted according to their contribution to a $\alpha = -2.4$ Salpeter Initial Mass Function, IMF. The combined spectra approach probably pushes the upper mass cutoffs to higher values.

5. MOLECULAR HYDROGEN

ISO offers the unique opportunity to study H_2 through its rotational lines and thus to get direct estimates of the molecular hydrogen mass in galaxies. In NGC 3256 ISO detected three rotational lines S(1), S(2) and S(5), whereas in Arp 220 and NGc 4038/39 the S(1) and S(5) transitions were detected. The mass of the 'warm' gas where the lower transitions originate, is found to be of the of the order of few$\times 10^8$ $M_\odot$ or even up to 3×10^9

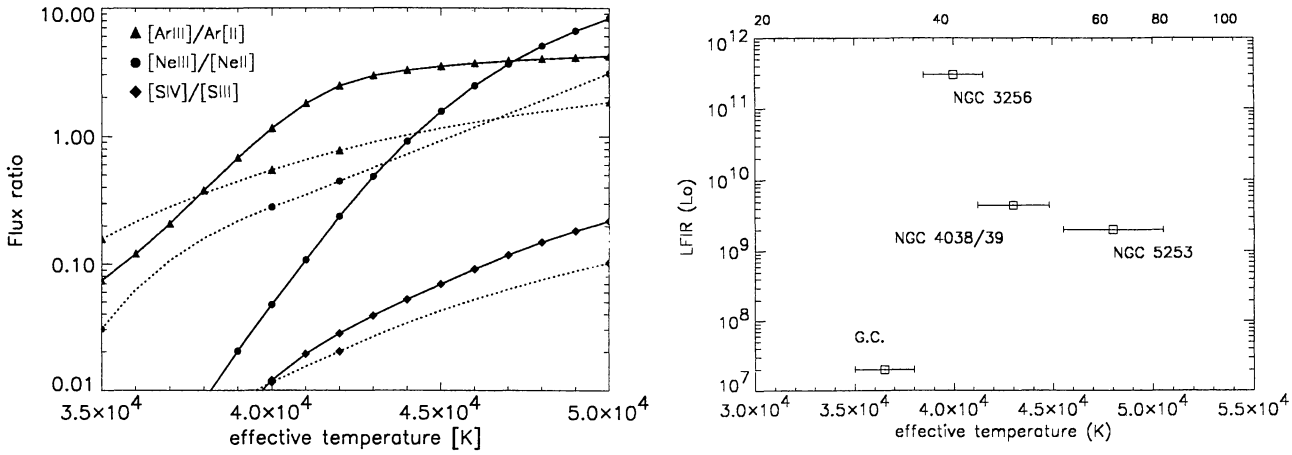

Fig. 2. (left): Plot of fine structure line ratios vs the effective temperature of the ionizing single star. Continuous line corresponds to Kurucz, dotted line to Sellmaier models. (right): Plot of the far-infrared luminosity L_{FIR} versus effective temperature T_{eff} of the ionizing radiation field. The equivalent upper mass cutoff for the simplified case of single star is also shown.

in the case of Arp 220. Comparing the current 'warm' mass estimates with those mass estimates derived from CO measurments we conclude that warm molecular gas is always several % of the total molecular mass as this is probed by CO observations.

6. SUMMARY

We have presented first results from the ISO-SWS multi-line spectroscopic studies in a number of galaxies. Based on fine-structure line ratios we investigated the physical conditions of the ionized gas and also the stellar content of the galaxies. The infered effective stellar temperatures T_{eff} and upper mass cutoffs are higher than previous estimates.

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